INVESTIGATION OF A HIGH VOLTAGE, HIGH FREQUENCY POWER CONDITIONING SYSTEM FOR USE WITH FLUX COMPRESSION GENERATORS*

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Abstract

The University of Missouri-Columbia is developing a compact pulsed power system to condition the high current signal from a flux compression generator (FCG) to the high voltage, high frequency signal required for many pulsed power applications. The system consists of a non-magnetic core, spiral-wound transformer, series exploding wire fuse, and an oscillating mesoband source. The flux compression generator is being built by Texas Tech Univ. and is designed to drive inductive loads on the order of microhenries rather than a nanohenry load often driven by FCGs.

The power conditioning transformer consists of a 1 μH primary winding inductance and a turns ratio of 1:3 with a coupling factor between .75 and .85. Use of the transformer and a crowbar switch to minimize the peak voltage across the fuse allows the fuse length to be reduced without risk of an arc breakdown. The fuse was designed to interrupt a peak current of 25 kA – 40 kA in less than 500 ns. The multiple stage fuse is constructed using two sections with an effective length of less than 25 cm. A capacitance of about 275 pF connected to the transformer secondary is charged to a voltage around 200 kV. The capacitor is then switched into an underdamped resonant circuit to generate an RF signal.

A non-destructive test stand has been built to simulate the output current of a flux compression generator and allow inexpensive and repeatable testing of the power conditioning components. This paper includes a description of the test stand, pulse transformer, exploding wire fuse, and oscillating circuit along with experimental results obtained with the non-destructive test stand.

I. INTRODUCTION

The University Consortium for High Power Microwave Integration is a collaborative effort including Texas Tech University (TTU), the University of Missouri-Columbia (UMC), and the University of New Mexico focusing on the integration of flux compression generators (FCGs), power conditioning components, and RF sources. The University of Missouri-Columbia is developing and testing a power conditioning system similar to that proposed by Reinovsky [1]. The full system, pictured below in Fig. 1, consists of an FCG or FCG simulator as a current source (L_{FCG}), a non-magnteic core, spiral-wound transformer (L_{pri} and L_{sec}), an exploding wire fuse (R_{fuse}), and an oscillating load (C_{store} and L_{shunt}) as its main elements. An antenna is currently being integrated with the system to radiate the RF signal, and a crowbar switch (S_C) has recently been added to improve fuse performance.

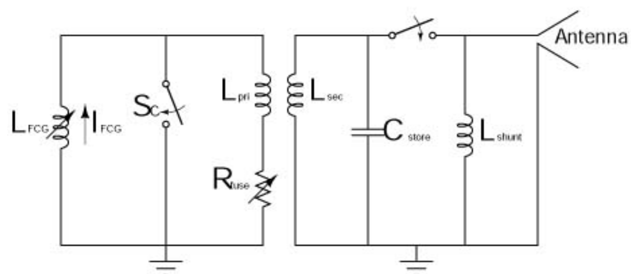

Figure 1. Full System Schematic.

II. POWER CONDITIONING COMPONENTS

A. FCG Simulator

An on-campus test stand was necessary for the several power conditioning components to be repeatedly and cost-effectively tested. The test stand was designed to produce the nearly exponential current rise of an FCG. Unlike a simple capacitive discharge in which the peak current occurs at zero dI/dt, it is desired that the current reach the desired peak value while the rate of current rise is still high. Two methods of simulating this waveform were demonstrated by Belt, and a system based upon

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14. ABSTRACT

The University of Missouri-Columbia is developing a compact pulsed power system to condition the high current signal from a flux compression generator (FCG) to the high voltage, high frequency signal required for many pulsed power applications. The system consists of a non-magnetic core, spiral-wound transformer, series exploding wire fuse, and an oscillating mesoband source. The flux compression generator is being built by Texas Tech Univ. and is designed to drive inductive loads on the order of microhenries rather than a nanohenry load often driven by FCGs. The power conditioning transformer consists of a 1 ìH primary winding inductance and a turns ratio of 1:3 with a coupling factor between .75 and .85. Use of the transformer and a crowbar switch to minimize the peak voltage across the fuse allows the fuse length to be reduced without risk of an arc breakdown. The fuse was designed to interrupt a peak current of 25 kA 40 kA in less than 500 ns. The multiple stage fuse is constructed using two sections with an effective length of less than 25 cm. A capacitance of about 275 pF connected to the transformer secondary is charged to a voltage around 200 kV. The capacitor is then switched into an underdamped resonant circuit to generate an RF signal. A non-destructive test stand has been built to simulate the output current of a flux compression generator and allow inexpensive and repeatable testing of the power conditioning components. This paper includes a description of the test stand, pulse transformer, exploding wire fuse, and oscillating circuit along with experimental results obtained with the non-destructive test stand.

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magnetically switched parallel inductors was built at UMC [2].

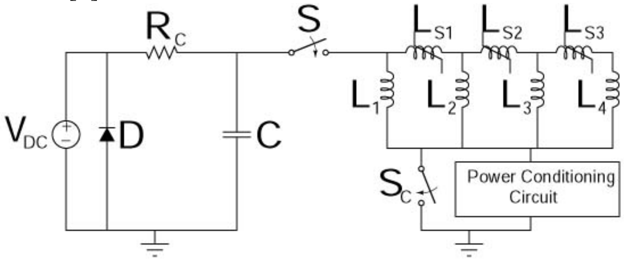

Figure 2. Basic schematic of FCG simulator with power conditioning components and crowbar switch.

Figure 2 above displays the basic schematic for the FCG simulator. A high voltage capacitor is discharged through the network of parallel inductors in which $L_1 > L_2 > L_3 > L_4$. The inductors L_{S1}, L_{S2}, and L_{S3} are saturating magnetic cores that sequentially switch the parallel inductors into the circuit. One way in which the UMC simulator differs from that investigated by Belt is that the UMC simulator is designed to drive an external inductive load, specifically the transformer inductance. Therefore, the simulator at UMC was designed to have a minimal inductance after all of the cores had saturated.

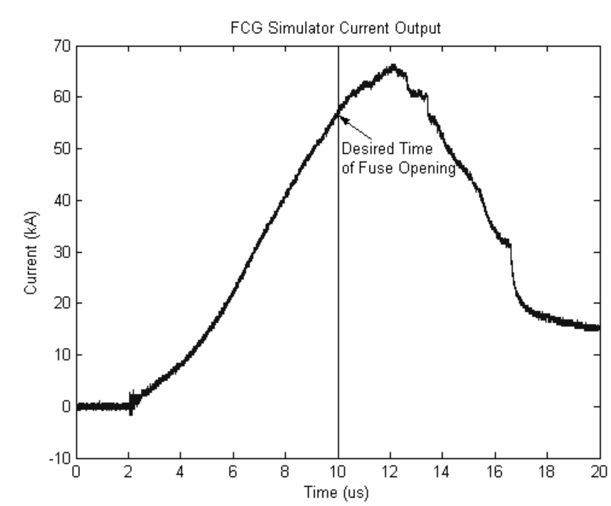

Figure 3. Current waveform from FCG simulator

Figure 3 shows a typical current rise from the FCG simulator, demonstrating the effect of the decreasing circuit inductance on the rate of current rise. A current rise time of in the range of 8-10 μs was desired to replicate the previous TTU FCG experimental results [3]. The vertical line placed 8 μs after the beginning of current rise represents the time at which the fuse would be designed to open. The data in Fig. 3 was taken without a transformer or fuse load, resulting in a peak current after 8 μs between 55 kA and 60 kA. The addition of the power conditioning components reduces this peak current to between 30 kA and 40 kA.

B. Pulse Transformer

The pulse transformer was designed following the concepts of Martin and Rohwein [4]. The transformers utilized a spiral-strip geometry with a non-magnetic core. The windings were made of tapered copper foils and mylar insulating sheets. The outer diameter of the transformers is approximately 15.25 cm, and the length of the transformers is approximately 17.78 cm.

The FCGs produced for this system were designed to operate into microhenry loads, so the minimum transformer primary self-inductance was designed to be 1 μH. A turns ratio of 1:3 was chosen to allow the transformer-fuse components to drive a low impedance RF load if necessary. For the system described in this paper with a high voltage capacitive load, the turns ratio can be increased. The coupling factor is decreased due to the use of a non-magnetic core transformer, but coupling factors up to .85 have been achieved with the present construction techniques. The transformers therefore enable an effective voltage step-up of up to 2.55. This effective step-up ratio could be increased much further by increasing the turns ratio for capacitive loads while only minimally increasing the leakage inductance. Figure 4 shows an example transformer.

Figure 4. Spiral-strip pulse transformer.

C. Exploding Wire Fuse

The opening switch was implemented as a two-section array of parallel wires. Between 20 and 36 wires were used, depending on the desired action integral before opening. Forty gauge silver-plated copper wires with a 6.1% plating thickness were chosen based on previous fuse wire studies [3].

The wires are angled in each of the two sections of the fuse. Copper field shapers provide the form on which the wires are angled. Since the final fuse resistance is directly proportional to the wire length, angling the wires allows a longer effective fuse length in a shorter package. The spacing between the top and bottom field shapers ranged from 15.24 cm to 30.48 cm, depending on the required fuse voltage holdoff. The entire assembly was packaged in a 15.24 cm cylinder with very fine glass beads as a quenching medium. The glass beads were rated with a mesh size of 170-325.

Figure 5. Fuse showing wires and field shapers (left) and being assembled with fine glass beads (right).

D. RF Circuit

The oscillating load circuit consists of a storage capacitor, oil spark gap switch, and a low inductance shunt. The capacitor was made in a tri-plate geometry for this demonstration. Double-sided PC board and polyethylene insulators were used to construct the capacitor. The capacitor was designed to be about 275 pF and hold off hundreds of kilovolts in an oil bath.

A low inductance oil spark gap was utilized to short the capacitor through a shunt inductance. The shunt inductance consisted of a copper sheet approximately 15 cm wide, running the length of the capacitor. A resistive load of approximately 369 ohms was placed in parallel with the capacitor for voltage measurements. When the oil gap closes, an underdamped resonant circuit generates an RF signal. The load circuit can be seen in Figs. 6 and 7.

E. Crowbar Switch

The inductance of an FCG is a minimum at the end of its operation, at the peak current output. As previosly mentioned, the FCG simulator was designed to also have a minimal inductance at the time of peak current. However, experiments proved that the inductance of the FCG simulator at the time of fuse opening was non-negligible. As a result, there was a very significant additional voltage across the fuse as the current was interrupted. The resulting restrike on many of the experiments did not allow the fuse to fully open. Since the energy stored in the inductance of the FCG or FCG simulator at the time of fuse opening is not coupled into the secondary storage capacitor, it was determined that a crowbar switch was required to divert this energy. With the crowbar switch in place, the voltage across the fuse at the time of the fuse opening should approximately equal the voltage across the transformer primary winding. The crowbar switch was implemented as a simple atmospheric pressure air spark gap. The spacing of the switch was adjusted between 1 cm and 2 cm to ensure that the spark gap did not close before the fuse opened.

III. EXPERIMENTAL RESULTS

Many experiments were conducted to optimize the various power conditioning components. Final tests were aimed at full system operation with a current input similar to that expected from a Texas Tech FCG. An antenna was not used in the experiments being presented here. The experimental setup is shown in Figs. 6 and 7.

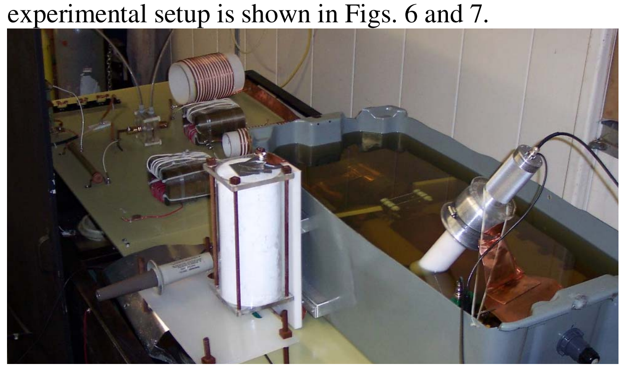

Figure 6. Integrated test setup: Power conditioning components at lower right with FCG simulator at upper left.

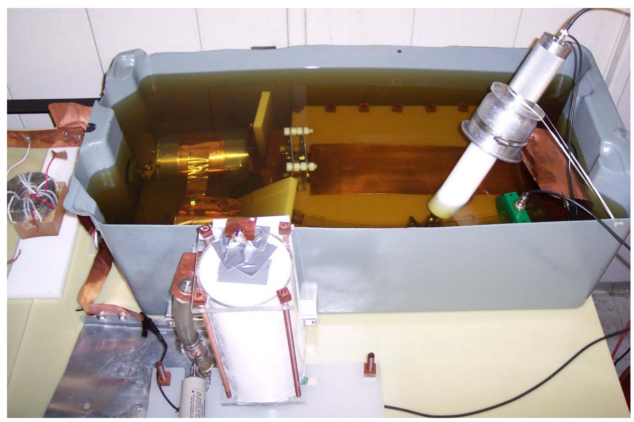

Figure 7. Power conditioning components: Transformer, oil spark gap, and RF circuit in oil bath with fuse mounted externally.

For these experimental results, a 30.48 cm fuse consisting of 28 wires and an oil gap spacing of approximately 1.1 mm were used. The transformer had a 1 μH primary and an 8.25 μH secondary self inductance. With a coupling factor of .8, the effective step up ratio was about 2.3. A resistive load of 369 ohms was placed in parallel with the 275 pF storage capacitor for voltage measurements. As shown in Fig. 8, the peak current generated was over 32 kA after approximately a 12 μs rise time. The current dropped to around 20 kA in about 150 ns before the oil gap switch on the secondary closed and the RF signal was generated into the load. As is shown in Fig. 8, the secondary RF oscillations are coupled to the

primary circuit, resulting in large fluctuations in the fuse current. The current in the transformer primary crosses zero within 200 ns of the beginning of the current interruption. The current is briefly reversed. However, this is after the RF signal on the secondary circuit has been delivered to the load. Analysis of the current data indicates that the fuse opened at about 6000 A^2s.

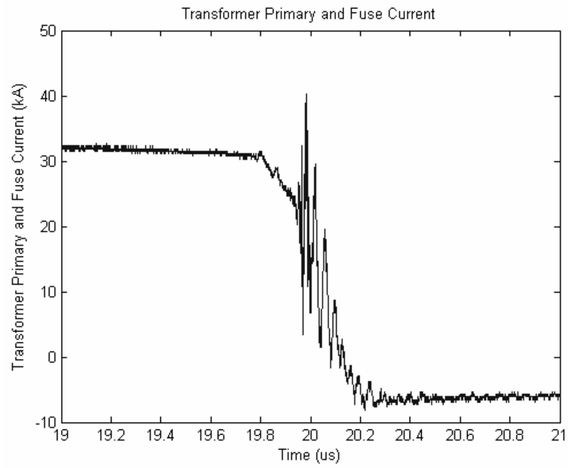

Figure 8. Detailed view of current interruption by fuse.

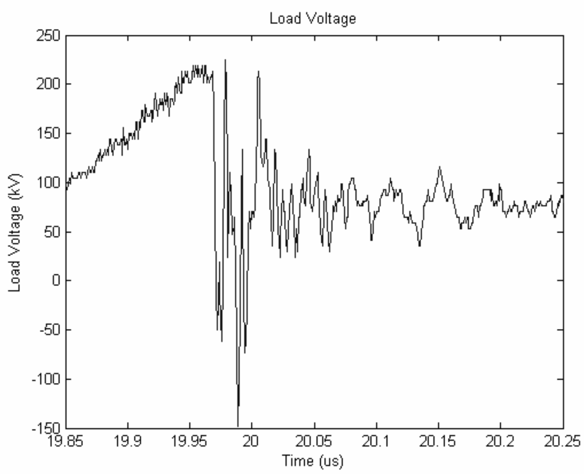

Figure 9. Load voltage at time of fuse opening.

The voltage across the load capacitor is shown in Fig. 9. As the fuse quickly decreases the primary current from 32 kA to about 20 kA, the capacitor is charged to over 200 kV. The oil gap closed, resulting in the several oscillations that follow. The peak RF power was greater than 130 MW. There is a wide band of frequencies present in the secondary RF oscillations. As seen in Fig. 10, there is significant frequency content up to about 250 MHz. The frequency content up to 250 MHz was consistently measured in several experiments.

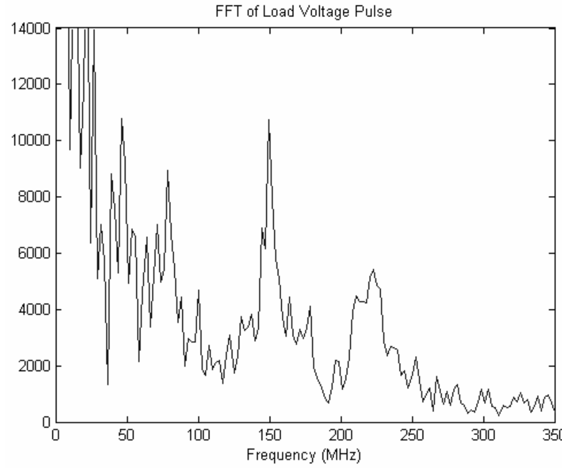

Figure 10. Frequency content of load voltage oscillations.

IV. SUMMARY

A complete power conditioning system for use with flux compression generators has been investigated. The power conditioning system has been shown to be capable of voltages above 200 kV and oscillates in a frequency band extending up to 250 MHz. Peak powers above 130 MW have been consistently demonstrated as well as power levels above 250 MW.

Future work on this system will involve increasing the peak voltage by increasing the oil dielectric spark gap electrode spacing and optimization of the crowbar switch. The shunt inductance in the resonant circuit will also be dramatically reduced to increase the high frequency content. Designs have been prepared to significantly reduce the size of the capacitor geometry for integration with the other power conditioning components. Additional tests of the power conditioning system along with an antenna and FCG are being discussed.

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